Exhibit G

A DECADE OF MEMS AND ITS FUTURE

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ABSTRACT

This paper deals with a history of microelectromechanical system(MEMS) development in this decade. An overview of the MEMS research topics is also given. The topics include microactuators, microsensors, micro miniature motion-systems(e.g. microrobots), applications and the fabrication technology involved. MEMS is supposed to contribute the 21th Century society in three major areas such as (1) wider distribution of and easier access to information, (2) compatible lifestyle with environment and (3) improvement in social welfare. The technological issues for future development of MEMS are discussed.

INTRODUCTION

Making small machines which are almost invisible has been one of the dreams of mankind. Such machines, so called microelectromechanical systems(MEMS) in US and micromachines in Japan, are composed of both mechanical devices and electrical devices. While electrical devices such as sensors and electronic circuits were well established technically, the study of mechanical devices such as micro mechanisms and microactuators began only a decade ago when the MEMS workshop was started. Since then, researchers have achieved remarkable progress. The successful fabrication and operation of microactuators and micro mechanical parts by IC-based micromachining technology enabled us to produce MEMS[1-3]. Although the small size of mechanical components of the system is a very distinctive feature of this emerging technology, it has other, maybe even more attractive, features. The three characteristic features or the three "M"s of the technology are[2]:

Miniaturization
Multiplicity
Microelectronics

Miniaturization is clearly essential. However, the mere miniaturization of macroscopic machines is not possible because of the scaling effect. Like a swarm of ants carrying a large food, cooperative work of many micro elements can perform a large task, even when one single device can only produce small force or perform simple motion. Multiplicity is the key to successful micro systems. The integration of microelectronics is essential for micro moving elements to cooperate with each other and to perform a given task.

In order to realize MEMS with above mentioned features, fundamental technological issues are materials, machining processes and devices. There are two kinds of machining processes; one is based on semiconductor technologies and the other on mechanical means. Devices include sensors, actuators and integrated circuits. Detailed research items in these issues are shown in Fig. 1.

Using these technologies in Fig. 1, we may utilize MEMS in some applications. Figure 2 shows the prospective applications in optics, transportation and aerospace, robotics, chemical analysis systems, biotechnologies, medical engineering, microscopy using scanned micro probes. Most of the applications have a common feature in that only very light objects such as mirrors, heads, valves, cells and microprobes are manipulated and that little physical interaction with the external environment is necessary. One reason is that present microactuators are still primitive and large forces cannot be transmitted to the external world. The other reason is difficulty in packaging.

The micromachining technology has quite a long history. Table 1[3] summarizes major inventions before 1987 when MEMS workshop started. Achievements after 1987 are listed in Table 2 together with the names of places of MEMS Workshops and Transducers Conferences. Papers presented at MEMS Workshops are included as much as possible while those at Transducers Conferences are very limited because of the space. Also, reference to each paper is not addressed. Papers are categorized in accordance with the items shown in Figs. 1 and 2.

DEVICES AND TECHNOLOGIES

Materials for MEMS

Silicon is the most commonly used material in micromachining[4] because (1)the process is well established, (2)it has good mechanical properties, and (3)integration with electronic and sensors is possible. Other materials have also been used for specific purposes in micromachining. Table 3 summarizes the materials and their useful characteristics. It is important to develop batch fabrication processes for all the materials in the table, so we will reiterate features of micromachining.

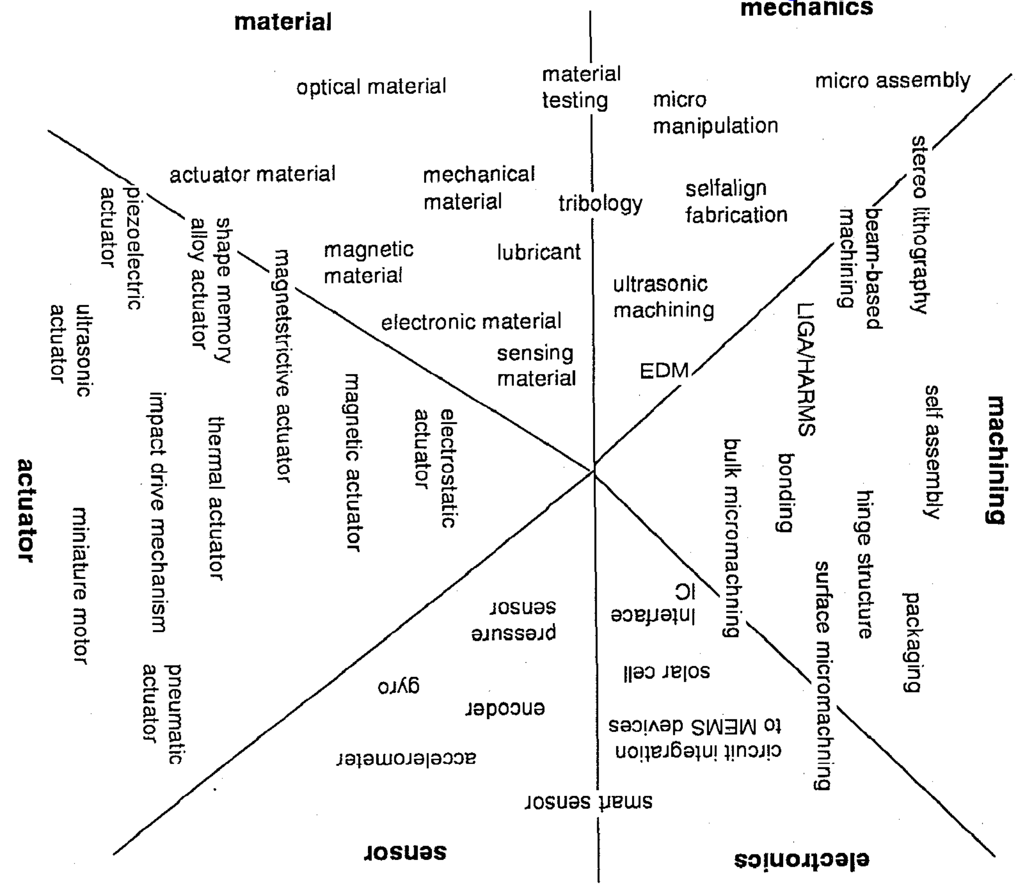

Fig. 1 A map of MEMS devices and technologies

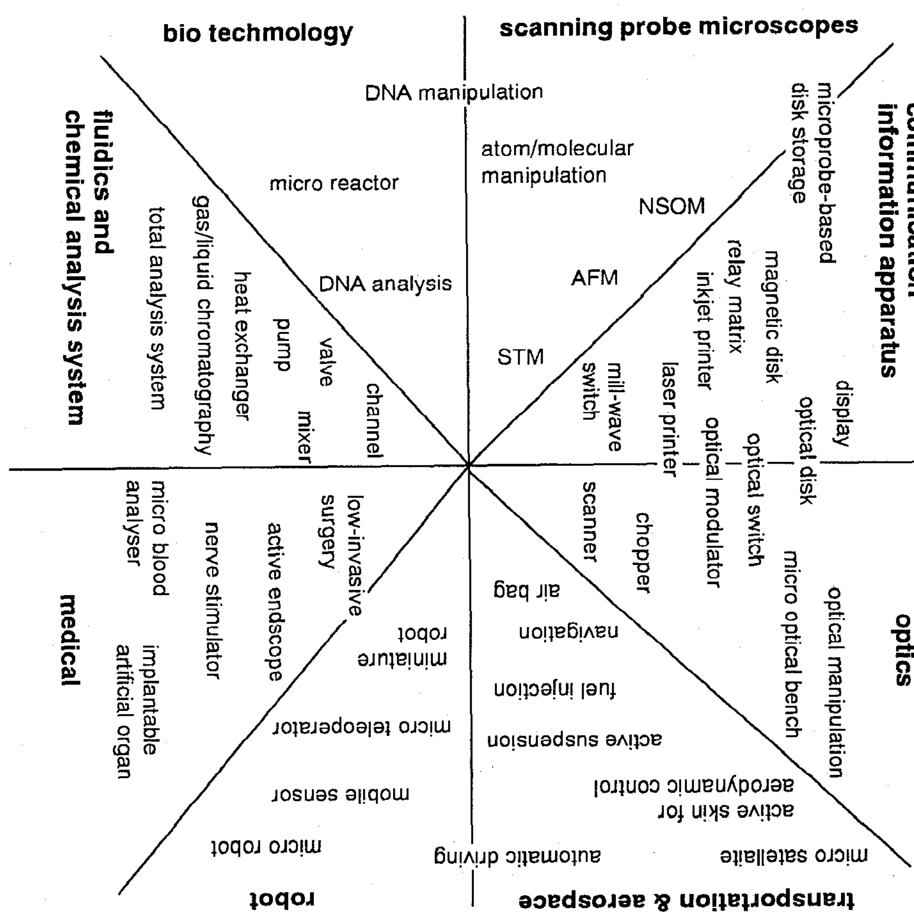

Fig. 2 A map of MEMS applications

Table 1 History of micromachining (before 1986)

19 C.	photo reproduction and printing
1951	shadow mask for CRT (RCA , USA) <photofabrication>
1954	piezoresistive effect
1962	crystalline oriented anisotropic etching
1963	silicon pressure gauge (Toyota Central R&D Lab, Japan)
1967	oscillating gate transisitor (WH, USA) <sacrificial layer etching>
1969	dopant dependent etching stop
1970	Si micro electrodes (Stanford Univ, USA) <Si micro structure>
1973	Si pressure sensor for catheter (Stanford Univ, USA) micro ISFET (Tohoku Univ, Japan) <sensor packaging>
1975	integrated gas chromatography (Stanford Univ, USA) <sensor + micro structure>
1979	integrated pressure sensor (Univ. Michigan, USA) <sonsor + circuits>
1981	quartz micro mechanism (Yokogawa, Japan)
1982	LIGA process (KfK, Germany) <high aspect ratio micro structure>

Micromachining

Microstructures fabricated by surface micromachining are planar in nature and have thickness of up to 10 μm in most cases. Some applications require thicker structures or three-dimensional-complicated structures. LIGA process utilizes deep X-ray lithography, electroplating and molding to make thick structures. UV-lithography with special resist, photosensitive polyimide and deep reactive ion etching (RIE) have also used to make high aspect ratio (the ratio between height and width of a structure) microstructures and mold. If plated metals are used to make replicas, resulted structures are called HARMS, meaning high aspect ratio metallic structures. Poly-silicon by LPCVD (low pressure chemical vapor deposition) can used to have replicas. Wafer bonding technologies have developed to build 3-D structures.

Modifications of surface micromachining have been attempted, too. One technique is to fold up micromachined plates from the substrate to construct a 3-D structure. The plate is released from the substrate and reconnected by hinges, flexible films or even active hinges made by conductive polymers. Such structures as a corner cube reflector and a micro "ant-based robot" were fabricated. In other trials, overhanging structures were made. Microscopic tweezers made of polysilicon protrude 0.4 mm from the edge of a hole. A single-celled protozoa, a euglena, was held by this microgripper.

Electron beams, laser beams or ion/atomic beams can assist selective growth/solidification/etching of materials. Three-dimensional structures in arbitrary shapes can be fabricated. Lithography on 3-D surfaces is possible. Mechanical processes such as electro discharge machining(EDM), ultrasonic machining and gliding for micro structures have also demonstrated. Sometimes such machining processes require parts handling; for this micro manipulation is studied. Unfortunately there is a trade-off between batch fabrication capability and 3-D complicated machining capability.

Microactuators

A microactuator is the key device for MEMS to perform physical functions. Because of the scaling consideration[5,6], the electromagnetic force which is most commonly used in the macro actuators is not the only driving force for microactuators but also many microactuators utilizes other driving principles such as the electrostatic force, piezoelectric force, shape memory alloys and thermal expansion.

Each actuation principle has its own advantages and disadvantages. The choice and the optimization should be made according to the requirements of applications. Generally speaking, the electrostatic actuator is more suitable to perform tasks which can be completed within a chip (positioning of devices/heads/probes, sensors with servo feedback, light deflection and modulation, etc.), since it is easily integrated on a chip, easily controlled and consumes little power. On the contrary, the other types of actuators are more robust, produce large force and are suitable to perform external tasks (propulsion, manipulation of objects, etc.).

Table 3 Materials in Micromachining

material	usage	characteristics
polyimide	structure	soft & flexible, optical guide
tungsten	structure	not attacked by HF
Ni, Cu, Au	structure	plated thick structures
quartz	actuation	anisotropic etching, piezoelectric
ZnO	actuation	piezoelectricity
PZT	actuation	large piezoelectricity
TiNi	actuation	shape memory allay
GaAs	optics	LASER, LED, detector
DLC	lubrication	low friction & wear

Table 2 History of MEMS research topics

	1987	1988	1989	1990	1991	1992
MEMS Workshop		Hyannis	Salt Lake City	Napa	Nara	
Transducers Conf.	Tokyo		Montreux		San Francisco	
machining	micro gear & turbine		desolved wafer process		LIGA w/sacrificial layer lithography on 3-D surface hinge structure	
electronics					proposal for integrated MEMS	
mechanics		impact drive material test methodoogy	membrane load-deflection test fracture toughness test	micro EDM frictiontest device CAD	micro tweezer teleoperator for nano scale	
material	poly- silicon	CVD tungsten	ZnO	GaAs Mo TiNi(SMA)	diamond like carbon film PZT	
sensor	servo feedback accelerometer	pressure/acceleration switch		electron tunneling sensor		
micromachined actuator * hybrid assembled	thermo-bimorph electrostatic rolling*	electrostatic micromotor	superconductive levitated* wobble motor* comb-drive	ultrasonic electrostatic film* air levitation stage wobble micromotor	cybernetic actuator* flexible pneumatic* magnetic*	
optics			SMA driven opticalfiber switch		optical encoder electromagnetic opticalfiber switch	
communication & information apprts					milli-wave switch & filter	
scanning probe microscopes			micro STM (ZnO cantilever)	positioning based on STM		
robot		master/slave tweezer	1 cubic inch robot		magnetostrictive mover in pipe	
medical equipment					nerval pickup array micro velcro	
fluidics & chemical analysis systems	integrated mass flow contoller thermal ly driven micro valve	thermo-pneumatic pump	pump & noramlly close valve flow in microchannel	rrayed valve electrohydrodynamic pump pump & 3-way valve integration		
bio technology		cell handling & fusion system	arrayed vessel for cell fusion			
transportation/ aerospace						

Table 2 History of MEMS research topics (continued)

1992	1993	1994	1995	1996	1997
Travemuende	Fort Lauderdale	Ohiso	Amsterdam	San Diego	Nagoya
	Yokohama		Stockholm		
HARMS beam assisted 3-D process low temperature bonding	deep RIE stereo lithgraphy dry release	fluidic self-assembly	active hinge structure assemble by bonding microactuated 3-D construction	2-D self-assembly microprobe assisted 3-D structure	
bonding for integrated sensor	rechargable battery	solar cell array wafer through hole connection actuator/circuit integration		ASIC motor controller field emmitter w/ thin film transistor	
		3-D process by FAB & micromanipulation	self-aligned machining	pick/place construction micro device for material testing	
		fluorocarbon film magnetostrictive film		permanent magnet film	
	gyro scope	multi-axis servo-accelerometer			
S-shape electrostatic	scratch drive quartz piezo arrayed air nozzle distributed electrostatic electromagnetic motor	buckeling-based			
	fiber aligner vari-focus mirror light modulator array arrayed mirror display	adjustable external cavity laser laser manipulation micro free space optics	tunable IR filter grating scanner	scanner by hinge structure mirco optical disk	
actuator for HDD slider	matrix relay micromotor for HDD microdisk			actuator for HDD head mercury relay	
lateral tunneling unit			NSOM/AFM probe	micro AFM cantilever array	
insect-based robot	ciliary motion conveyer	pipe inspection robot	swimming robot? flying robot		
			multi-link active catheter		
	mixer liquid dosing system	3-D channel by stereo lithography	valveless pump microchannels for cooler	screech control of jet modular device for micro chemical analysis	
DNA handling	neuron cell culture		DNA handling & modification	electrophoresis stage w/ on-chip detector	
micro instrument for spacecraft			actuator for delta-wing control	fuel atomizer	

Electrostatic micromotors/actuators

The first electrostatic micromotors with diameters of 60-120 μm were developed by L.-S. Fan, Y.-C.Tai, and R.S. Muller [7]. It is called a side-drive type motor, since it utilizes the electrostatic force which acts between the edges of the rotor and the stator both made with polysilicon. Rotational speed was on the order of 500 rpm. The speed is relatively low because the friction between the rotor and the shaft, although a silicon nitride film was deposited on the sliding surface to reduce the friction. Later improvement by Mehregany, et al.[8] enabled the rotational speeds up to 15,000 rpm and continuous operation for more than a week. They reduced the clearance between the rotor and the shaft, formed three dimples under the rotor for both support and electrical contact.

Even for the improved micromotors, friction was a major problem. One solution is to replace the sliding contact at the center with rolling contact. A rotor is a smooth ring and, by electrostatic attraction, rotates eccentrically without slipping at the contact with shaft. Since the circumferential distance of the rotor hole is slightly longer than that of the shaft, the rotor really revolves a fraction of a circle after one eccentric rotation. This results in two advantages of the motor, e.g. reduction of friction and higher torque at low speed. The usage of rolling motion in many geometries was demonstrated, although fabrication processes for these actuators were not IC based nor fully IC-compatible.

Another way to avoid the effects of friction is with elastic supports. The most popular one is a comb-drive actuator. It is supported by double-fold beams and actuated by interdigitating comb-like structures. The electrostatic force to increase the overlapping is generated when voltage is applied between the suspended and fixed combs. Typical displacement is 10 μm and the force is 10 μN.

Other Driving Principles

Microactuators which utilize such driving principles as piezoelectric, shape memory alloys, thermal expansion(gas, liquid, solid) and electromagnetic have been developed. In terms of reducing friction, most of them moves elastically with some exceptions. The ultrasonic micromotor/actuator utilizes the standing wave to drive the rotor/slider. Vibrations of cantilevers can carry objects. Levitation by repulsive force between the permanent-magnet and the superconducting material, by air pressure from small holes and controlled electrostatic force was demonstrated. Controlled air flow from micronozzles could 1 carry a flat object as well as levitation. Recoil of a small mass which is moved quickly by piezoactuator can drive a main body in a step wise manner. The position of the main body is kept still by static friction.

Arrayed actuators

If we want to have MEMS to perform a macroscopic task, the key idea is to coordinate simple motions of many microactuators. Even when each moving step is small, accumulation of many steps covers large distance. A heavy load may be distributed among many actuators which produce only small force. Flexibility of motion, expandability and immunity against failure of elements can be achieved. One of the major problems in present microactuators, the problem of friction can also be solved. Friction in micro scale prohibits us from using gears and joints because they waste too much energy. Suspended actuators do not suffer from friction but have limited motion range up to a few tens of micrometers. If many such microactuators are arranged in series and parallel, the overall structure can produce larger force and displacement and perform more complicated functions than each simple actuator. Because these actuators are driven directly, energy loss associated with transmission of motion is minimal. They can even utilize the friction between an object and them to transmit driving force. Arrays of micro valves, electrostatic actuators with many small force generating elements, arrays of cantilever actuators which vibrate in synchronization and convey objects and a in-plane conveyance system using controlled air flow from arrayed nozzles on the substrate were operated successfully. A projection display based on arrayed movable micromirrors is commercialized. Miniaturized electromagnetic relays are arrayed for telephone switching.

APPLICATIONS

Optics

Petersen, et al.[4] demonstrated deflecting light beams by small cantilevers driven by electrostatic force in 1977. Since then, optical-fiber switches, its aligner and an adjustable miniature Fabry-Perot interferometer which acted as a tunable filter, an external cavity for laser diode and a passive modulator were reported. Integrated optic technology was used to fabricate a one-chip optical microencoder. A display based on diffraction gratings was developed. Three-dimensional hinged structures were used to build free space optical systems on a silicon wafer.

Fluidics

This is another application with long research history. An integrated mass flow controller was developed ten years ago. Integrated micro dosing systems were built. Chemical analysis systems are under intensive study. The control of macro aerodynamics, e.g. formation of vortex, by microactuators on the surface or around a nozzle has demonstrated. The positive growth of the disturbance given by a small motion microactuator enable effective control of macroscopic phenomena.

Communication and Information Apparatus

Many optical MEMS devices have been developed for communication systems, especially for fiber-communication networks. MEMS displays based on

movable mirrors and micromachined filed emitter arrays were developed. One of the earliest and the most successful application of MEMS is the thermal ink jet printers. In hard disk data storages, sliders, suspensions and actuators for fine tracking have been fabricated by micromachining technologies. Micro optical disk was also tried. In the near future, data storage devices using scanning micro probes and input/output devices for virtual reality and other human/computer interfaces will be develpoed.

Biotechnology

The typical dimensions of biological objects are around 1-10 μ m for cells and nano meters in thickness by microns in length for macro molecules. The electric field distribution obtained by microfabricated electrodes can be controlled in the same order of the objects and is suitable for manipulating them. Washizu, et al.[9] developed a cell fusion system using both a micro fluidic system and manipulation with the electric field. They also succeeded in orienting DNA molecules along the field and modify them by enzyme attached to a laser manipulated bead. Arrays of small vessels for cell fusion and culture were fabricated. MEMS for DNA multiplication and detection are under development. Micro droplets can be delivered by a pump based on ink jet printing heads. It is also possible to manipulate a cell or molecule by using force of laser beam and chemical affinity.

Scanning probe microscopes

A micromachined STM (scanning tunneling microscope) composed of piezoelectrically driven cantilever was successfully operated to take the atomic image of a graphite surface. Another micro STM utilized electrostatic actuators. Tunneling current control devices have been applied to detectors for highly sensitive sensors. Arrays of AFM (atomic force microscope) cantilevers and STM cantilevers were fabricated and under test. STM probes are also useful for lithography in nm scale and growth of thin and sharp micro structures. Even an atom can be manipulated by SPM (scanning probe microscopes). Analysis of physical/chemical interactions based on observation of single atoms and fabrication of new compounds by so-called "atom craft" will be realized by micromachined SPM.

FUTURE SOCIETY AND MEMS

Major issues of society in the 21st century will be:
(1) wider distribution of and easier access to information,
(2) compatible lifestyle with environment, and
(3) improvement in social welfare.
MEMS, with above mentioned features, are expected to give technological breakthroughs for these issues. Breakthroughs would be in five folds: machine intelligence, downsizing and parallelism, biomimetics, informatics and environment monitoring / preservation.

In terms of machine intelligence, it is possible to supply high-performance sensors and processors in large quantity and to integrate them in machines. All the necessary functions i.e. sensing, judgment and motion, to make machines more intelligent, can be implemented in one place. An intelligent machine may have large numbers of such closed-loop MEMS embedded in it. Sensors gather detailed local information from external environment, integrated circuits process the information in-situ, and actuators return appropriate reactions with minimal delay. Since the reaction can be performed at high frequency and in parallel at many locations, accumulation of small motions of microactuators result in a big effect.

In biomimetics, machines which are composed of many MEMS could mimic behaviors of living organisms. A MEMS becomes a building block like a cell in our body. Flexible motion like a snake could be performed by connecting MEMS in parallel and in series. The size of microactuators are one to tens of micrometers, the same size of cells and biological macromolecules such as DNA. We will be able to manipulate cells and macromolecules freely by microsystems. Of course, medical applications such as low-invasive surgery and artificial organs require biomimetic MEMS.

MEMS will play a major role in informatics. Because information itself has no mass and size, the smaller machines are the better when they gather, handle, transport and store information. MEMS are indispensable to the future infrastructure for information exchange and storage because they have information processing capability in themselves. MEMS can also contribute to improve the quality and density of display and sensing. Followings are possible usage of MEMS.

ISSUES FOR FUTURE DEVELOPMENT

Application-pull

It is undoubted that MEMS will play a key role in various field in future. It is necessary, however, to find profitable commercial applications in a short time in order to accelerate research and development of MEMS. This is particularly essential for industries. MEMS research is supported mainly by governmental projects in US, Europe and Japan now. For the future development of the technology, investments in private sectors are indispensable. First generation products and matured prototypes are being introduced in the following areas:
(1) Information apparatus such as displays, printers and data storage devices,
(2) micro-optical devices for global communication networks, and
(3) micro liquid handling systems for medical analysis and environmental monitoring.
We have to increase the number of products in other areas while pushing above mentioned areas. For instance:

MEMS for smart homes: A future room may be equipped with MEMS to maintain amenity. Illumination, temperature, humidity, air flow and sound are controlled by MEMS embedded in walls. A MEMS for this purpose detects conditions of the room using its temperature sensor, humidity sensor, air flow sensor, infrared sensor and microphone. Electronic circuits in the system determine appropriate response based on sensor signals and information from neighboring MEMS. The effecters of the system such as a heater, a ventilator, a lamp and a speaker, which are all miniaturized and arrayed, can adjust the condition to achieve maximum amenity. Microsystems can also be utilized for security and safety surveillance. The total system will probably have adaptive capability to trim its performance in accordance with the owner's preference and habit.

MEMS for transportation and aerospace: Automobile has been and will be one of the major application field of MEMS. MEMS will be used not only to make cars smarter but also to realize intelligent transportation systems. Aircraft design may be drastically changed by the introduction of MEMS[2]. The initial size of vortices of air is in the order of a few tens of micrometers. Therefore, if arrays of MEMS each of which can detect and extinct the vortex are embedded on the surface of a aircraft, it is possible to reduce aerodynamic drag dramatically. The arrays can also generate drag intentionally to control the posture of the aircraft.

Size and weight are the most important limitation for a spacecraft. Microsystems can be utilized to reduce the size and weight of apparatus with maintaining the same functionality as conventional systems. The concept of microsatellites has been discussed recently[10]. One day, a MEMS equipped with micro sensors for space observation, processors, antennae, micro rockets and controllers, etc. may be fabricated on a substrate and launched, making a "flying wafer".

Technology-push

Devices such as micromotors and microactuators have been proven. It is necessary to demonstrate real MEMS composed of mechanical and electrical elements. For instance, a micromotor is useful only when it is connected to elements to drive and controlled precisely at desired speed. The design method and integrate fabrication technology of MEMS must be established.

A new area of micro science and technology(MSE) should be establish in order to provide the theoretical foundations for the development of micromachines. MSE is the extension of conventional science and technology toward the microscopic world. The scaling effect is one of the fundamental issues in building micromachines. The frictional force dominates the inertial force in micro scale and prevent micro gears or rotors from moving smoothly, if moving at all. Friction and tribology in micro domain must be well understood. There are more issues such as accumulation of data of material properties in micro scales, standard evaluation methods for MEMS, a convenient performance index for MEMS which is similar to "instructions per second" for computers and "design rules" for IC's, and advanced new materials for actuators, structures and sensors.

System architecture for MEMS

The integration of sensors, actuators and controllers lead to the concept of autonomous distributed micromachines(ADM) as a system architecture suitable for MEMS. An autonomous distributed system is a system which is composed of many smart subsystems called individuals. An individual can gather information with its sensors and through communication from neighboring individuals and sometimes from the overall system. It independently determines its behavior based on the information. The way they decide their behaviors is to cooperate each other in order to complete the objectives of the overall system. The ADM are composed of many smart modules working as individuals which are clever enough to control their own actuators and to cooperate with each other. Design, low cost fabrication and control issues of ADM should be studied.

CONCLUSION

MEMS will have profound impact in the future society. It is necessary to continue and enhance research activities in both fundamental and application-oriented areas. Fusion of knowledge in different disciplines is essential for well-balanced and accelerated growth of the technology. I strongly believe that the international collaboration in science and technology of MEMS together with healthy competition in their commercialization field will lead to gigantic success of MEMS. The author owes the part of the content to discussion with Dr. K. J. Gabriel at ARPA.

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